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ABSTRACT

Explored are two theoretical approaches that attempt to cope with omitted responses, that is, when an examinee omits (fails to respond to) an item and therefore the item response formula cannot be used. Preliminary considerations are discussed, and it is shown that a conveniently simple application of equivalent items leads to internal contradictions. A rigorous mathematical model for response or omission is suggested as a plausible alternative. Special cases of the model are investigated for insight into implementation of the model, but are not recommended for practical use. (Author/PN)

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MAXIMUM LIKELIHOOD ESTIMATION OF ITEM RESPONSE PARAMETERS WHEN SOME RESPONSES ARE OMITTED

Frederic M. Lord

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Two theoretical approaches are considered for dealing with omitted responses. A simple modification of the usual item response theory model leads to internal contradictions. An alternative model is suggested and some special cases are investigated.

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Maximum Likelihood Estimation of Item Response Parameters

When Some Responses Are Omitted

Abstract

Two theoretical approaches are considered for dealing with omitted responses. A simple modification of the usual item response theory model leads to internal contradictions. An alternative model is suggested and some special cases are investigated.

Maximum Likelihood Estimation of Item Response Parameters When Some Responses Are Omitted*

In item response theory, the frequency distribution of the responses of a single examinee to n dichotomous items is commonly given as

$$f(u_1,\ldots,u_n) = \prod_{i=1}^{n} P_i^{u_i} Q_i^{1-u_i} \qquad (1)$$

where $Q_i \equiv 1 - P_i$, P_i is the probability of a correct response by the examinee to item i, and where $u_i = 0$ or 1 denotes his score on the item. When the examinee omits (fails to respond to) an item, this formula cannot be used. The purpose of this article is to explore two theoretical approaches that attempt to cope with omitted responses.

Section 1 presents some preliminary considerations. Section 2 shows that a conveniently simple application of (1) leads to internal contradictions. Section 3 considers a possible rigorous mathematical model. Sections 4 and 5 show that this model yields very reasonable results in two special cases that are sufficiently simple to be already familiar to us.

Two conclusions are reached.

1) A simple modification of the usual item response theory model (1) does not apply when the examinee has the option of omitting or responding at random.

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2) A model containing five item parameters and two examinee parameters seems reasonable. Even if some of these parameters should prove difficult to estimate accurately in practical work, the model should be useful for clear thinking about omitted responses.

1. Preliminary Considerations

If test score is the number of right answers, an examinee who omits responses on a multiple-choice test necessarily lowers his expected test score. Mathematical modeling of such (usually irrational) behavior will not be attempted here.

We will deal instead with the case where the 'formula score' $x - W/(A - 1)$ is to be used, x being the number of right answers, W the number of wrong answers, and A the number of choices per item. In this case, the examinee who wishes to maximize his expected score should not omit any items on which his chance of success is greater than $1/A$. If he can do no better than a random guess on an item, his chance of success equals $1/A$ and his expected test score will be the same whether he omits the item or guesses at random. He may omit or guess at random, as he pleases. If an examinee is forced to respond to an item that he has omitted, his chance of success is assumed to be $1/A$.

Note that P_i in (1) represents what the statistician knows about item i before it is administered to a given examinee. After the examinee has read the item, he may know the correct answer with more or less certainty, he may be misinformed on the item and thus

answer incorrectly, or he may guess at random with chance of success $1/A$. One should not conclude in such cases that P_i is 1, or that it is 0, or that it is $1/A$.

2. The Case of Equivalent Items

Items are called equivalent when they have identical $P_i \equiv P_i(\theta) \equiv \text{Prob}(u_i = 1|\theta) \equiv P$ at all ability levels θ . We will consider the case where both the mathematical form of P_i and the numerical values of the (item) parameters defining P_i are known.

When P_i in (1) is replaced by P , the frequency distribution of the u_i becomes

$$f(u_1,\ldots,u_n) = P^{\Sigma u_i} Q^{n-\Sigma u_i} \quad . \tag{2}$$

Since $x \equiv \sum_{i=1}^{n} u_i$ is the number-right score, we see that when x is given, the distribution of u_i in (2) does not depend on θ . Thus (as is well known) when all items are equivalent, x is a sufficient statistic for estimating θ . Any inference about θ should depend only on x . The frequency distribution of x is the familiar binomial

$$f(x) = \binom{n}{x} P^x Q^{n-x} \qquad (x = 0,1,\ldots,n) \quad . \tag{3}$$

Suppose now that a given examinee will either omit a certain item or else choose his response at random. According to the model, if he chooses his response at random, his number-right score x will be distributed as in (2).

Suppose, on the other hand, he decides to omit this one item (and no others). Denote his number-right score on the remaining $n - 1$ items by k ($k = 0,\ldots,n - 1$). Let $g(k)$ denote the frequency distribution of k for this examinee. We hope to find the mathematical form of $g(k)$ so that we can use it to get a maximum likelihood estimator of θ .

Since his probability of success on the omitted items is $C \equiv 1/A$, there is a mathematical relation between $f(\ )$ and $g(\ )$:

$$\left.\begin{aligned} f(0) &= (1 - C)g(0) \quad , \\ f(k) &= Cg(k - 1) + (1 - C)g(k) \qquad (k = 1,2,\ldots,n - 1) \quad , \\ f(n) &= Cg(n - 1) \quad . \end{aligned}\right\} \tag{4}$$

If the $f(\ )$ are considered as known, the $g(\ )$ as unknowns to be determined, we have here $n + 1$ linear equations in n unknowns. Written in matrix form, (4) becomes

$$\begin{bmatrix} 1-C & & & & & \\ C & 1-C & & & & \\ & C & 1-C & & & \\ & & \cdots & & & \\ & & & C & 1-C & \\ & & & & C & \end{bmatrix} \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ \vdots \\ g_{n-1} \end{bmatrix} = \begin{bmatrix} f_0 \\ f_1 \\ f_2 \\ \vdots \\ f_{n-1} \\ f_n \end{bmatrix} . \quad (5)$$

It seems reasonable that $g(k)$ determined from (4) or (5) provides the likelihood function from which the examinee's θ may be estimated by maximum likelihood.

A standard investigation (for example, Aitken, 1944, Section 30) shows that these $n + 1$ linear equations have no solution (are mutually inconsistent) unless $P = C$. Thus, excluding the uninteresting case where $P = C$, when $f(\ )$ is given by (3) no possible frequency distribution $g(k)$ (for the examinee's responses to non-omitted items) can exist.

Model (1) can be applied by replacing omitted responses by random responses. This introduces additional error into the data, however. If omits are not replaced by random responses, the usual item response function model (1) cannot fit the data. We have only proved this for tests composed of equivalent items, but the conclusion is presumably general, especially since any test may contain a few items that are statistically equivalent.

3. A Model for Response or Omission

The discussion in Section 1 suggests the following model. Let $R_i(\theta_a)$ denote the probability that examinee a, at ability level θ_a, feels no preference for any of the available responses to item i: if he responds to item i, he will respond effectively at random. For brevity, we will say that $R_i(\theta_a)$ is the probability of (total) ignorance on item i. It may be thought of as the proportion of examinees at ability level θ_a who are ignorant on item i.

Let $P_i(\theta_a)$ denote the conditional probability that examinee a will respond correctly to item i given that he is not ignorant. Thus

$$P_i(\theta_a) \equiv \text{Prob}(u_{ia} = 1 | \text{not ignorant}) \quad .$$

If the examinee omits item i, we will denote this by $w_{ia} = 1$; if he responds to item i, $w_{ia} = 0$. Let ω_a denote the probability that examinee a will omit an item of which he is ignorant:

$$\omega_a \equiv \text{Prob}(w_{ia} = 1 | \text{ignorance}) \quad .$$

Since we are concerned with a single examinee, we will drop the subscript a. As before, let $C \equiv 1/A$ denote the probability of success by random guessing:

$$C = \text{Prob}(u_i = 1 | w_i = 0, \text{ ignorance}) \quad .$$

Let a bar above a symbol denote its complement, for example, $\bar{P}_i \equiv 1 - P_i$.

There are three exhaustive and mutually exclusive events, denoted by ($w_i = 1$), ($w_i = 0$, $u_i = 1$), and ($w_i = 0$, $u_i = 0$). The unconditional probability of omitting is clearly

$$\text{Prob}(w_i = 1) = \omega R_i \quad . \tag{6}$$

A correct answer occurs with probability $\bar{\omega}C$ when the examinee is ignorant and with probability P_i when he is not ignorant, so

$$\text{Prob}(u_i = 1, w_i = 0) = R_i\bar{\omega}C + \bar{R}_i P_i \quad . \tag{7}$$

Similarly,

$$\text{Prob}(u_i = 0, w_i = 0) = R_i\bar{\omega}\bar{C} + \bar{R}_i\bar{P}_i \quad . \tag{8}$$

The right sides of (6), (7), and (8) sum to 1, as they should.

The joint distribution of w_i and u_i ($i = 1,2,\ldots,n$) may be written

$$L = \prod_{i=1}^{n} (R_i\omega)^{w_i}(P_i\bar{R}_i + C\bar{\omega}R_i)^{u_i\bar{w}_i}(\bar{P}_i\bar{R}_i + \bar{C}\bar{\omega}R_i)^{\bar{u}_i\bar{w}_i} \tag{9}$$

for the permissible values of (w_i,u_i) . The log likelihood is then

$$\log L = \sum_{i=1}^{n} [w_i(\log R_i + \log \omega) + u_i\bar{w}_i \log(P_i\bar{R}_i + C\bar{\omega}R_i)$$

$$+ \bar{u}_i\bar{w}_i \log(\bar{P}_i\bar{R}_i + \bar{C}\bar{\omega}R_i)] \quad . \tag{10}$$

Equations for maximum likelihood estimation can be written down from (10).

The following is suggested as a possible, plausible implementation of this model:

1. The parameter ω varies across examinees but not across items.
2. $P_i \equiv P_i(\theta)$ is a three-parameter logistic or normal ogive function of θ with positive slope.
3. $R_i \equiv R_i(\theta)$ has the same general mathematical form as $P_i(\theta)$ but different parameters; in particular, the slope is negative, the lower asymptote is zero.

The foregoing will be assumed in the further discussion of this model.

There are five item parameters in the plausible implementation (three for P, two for R) and two examinee parameters (ω and θ). It may not always be practical to estimate this many item parameters. In any case, the model is an aid to clear thinking about the proper handling of omitted responses.

Some special cases of the model are considered in the remaining sections. The purpose is to gain further insight into the implications of the model. These special cases are <u>not</u> recommended for practical use.

4. Special Case: No Omitting

When $\omega = 0$, we must have $w_i = 0$, and (9) becomes

$$f(u_1,\ldots,u_n) = \prod_{i=1}^{n} p_i^{u_i}(1 - p_i)^{1-u_i} \qquad (11)$$

where

$$p_i \equiv P_i \bar{R}_i + C R_i \quad . \tag{12}$$

Since (11) has the same form as (1), we have here the usual item response theory model for dichotomous items, omits being barred, except that now the item response function has the special form given by (12).

This item response function $p_i(\theta)$ need not be a monotonic increasing function of θ. The lower asymptote of $p_i(\theta)$ is C; if c_i, the lower asymptote of $P_i(\theta)$, is less than C, the probability of success may decrease at first as θ increases, before finally increasing to the upper asymptote at 1. This is a desirable feature: Examinees with sufficiently low θ can only guess randomly, examinees with higher θ may be misinformed and may do less well than a random guess. Model (11) - (12) was suggested by Samejima (1979).

5. Special Case: Equivalent Items, Knowledge or Random Guessing

Under the knowledge-or-random-guessing assumption, the examinee either knows the answer to a particular item or guesses at random or omits it. For purposes of the present model, the assumption is represented by the case where $P_i(\theta) = 1$ for all θ.

When the test is composed of equivalent items, the subscript i can be dropped from functions of parameters. Denote the number of omitted items by $w \equiv \Sigma_i w_i$, the number of wrong answers by $W \equiv \Sigma_i \bar{u}_i \bar{w}_i$.

The log likelihood (10) is now

$$\log L = w \log R + w \log \omega + x \log(\bar{R} + C\bar{\omega}R)$$

$$+ W(\log \bar{C} + \log \bar{\omega} + \log R) \quad . \tag{13}$$

If we differentiate this with respect to ω and set the result equal to zero, we obtain the likelihood equation

$$\frac{w}{\hat{\omega}} - \frac{Cx\hat{R}}{\hat{\bar{R}} + C\hat{\bar{\omega}}\hat{R}} - \frac{W}{\hat{\bar{\omega}}} = 0 \quad . \tag{14}$$

where $\hat{\omega}$ and $\hat{R}$ denote maximum likelihood estimators.

The likelihood equation for θ is seen to be

$$\frac{\partial \log L}{\partial \theta} \equiv \frac{\partial \log L}{\partial R} \frac{\partial R}{\partial \theta} = 0 \quad .$$

or simply $\partial \log L/\partial R = 0$. It is convenient for some purposes to think of R itself as the ability parameter, since $R \equiv R(\theta)$ is a one-to-one monotonic transformation of the parameter θ .

The remaining likelihood equation is thus seen to be

$$\frac{w}{\hat{R}} + \frac{x(-1 + C\hat{\bar{\omega}})}{\hat{\bar{R}} + C\hat{\bar{\omega}}\hat{R}} + \frac{W}{\hat{R}} = 0 \quad . \tag{15}$$

The maximum likelihood estimators of ω and of θ (or R) are the roots of (14) and (15).

Rewrite (14) and (15):

$$\frac{w}{\hat{\omega}} - \frac{W}{\bar{\hat{\omega}}} = \frac{Cx}{C\bar{\hat{\omega}} + \bar{\hat{R}}/\hat{R}} \quad , \tag{16}$$

$$w + W = \frac{x(1 - C\bar{\hat{\omega}})}{C\bar{\hat{\omega}} + \bar{\hat{R}}/\hat{R}} \quad . \tag{17}$$

Eliminating $\hat{R}$ from these two equations, we have

$$w + W = \left(\frac{w}{\hat{\omega}} - \frac{W}{\bar{\hat{\omega}}} \right)\left(\frac{1}{C} - \bar{\hat{\omega}} \right) \quad .$$

Clearing fractions, we find the maximum likelihood estimator

$$\hat{\omega} = \frac{w}{w + W/(1 - C)} \quad . \tag{18}$$

Solve (17) to obtain

$$\frac{\bar{\hat{R}}}{\hat{R}} = \frac{x(1 - C\bar{\hat{\omega}})}{w + W} - C\bar{\hat{\omega}} \quad ,$$

$$\frac{1}{\hat{R}} = \frac{n}{n - x}(1 - C\bar{\hat{\omega}}) \quad .$$

Using (18),

$$\hat{R} = \frac{1}{n}\left(w + \frac{W}{1 - C}\right) \quad . \tag{19}$$

From (18) and (19),

$$\hat{\omega} = \frac{W}{n\hat{R}} \quad , \tag{20}$$

a very reasonable result. It says that the estimated proportion of omits equals the actual number of omits divided by the estimated number of items on which the examinee is totally ignorant. Similarly, from (19),

$$n\hat{R} = x - \frac{W}{A - 1} \quad , \tag{21}$$

where $A \equiv 1/C$. This shows that the estimated number of items known by the examinee is given by the usual 'correction for guessing' formula.

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